ESD-TR-66-83

MTR-113

THE ABILITY TO PREDICT LOW-ANGLE HEIGHT ERRORS WITH THE NBS SURFACE-CORRECTED MODEL ATMOSPHERE

JUNE 1966

Lyall G. Rowlandson

Prepared for
DEPUTY FOR ENGINEERING AND TECHNOLOGY
SENSORS AND ENVIRONMENTAL FACTORS DIVISION
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L. G. Hanscom Field, Bedford, Massachusetts

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Project 7010
Prepared by
THE MITRE CORPORATION
Bedford, Massachusetts
Contract AF19(628)-5165

ESRRE

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ABSTRACT

A comparison is made between values of radio ray bending which is calculated in two ways: one using a ray-tracing computation based on radiosonde data; and the other using the National Bureau of Standards exponential reference atmosphere (1959) corrected to match the refractivity measured at the surface. The refractivity data for the ray-tracing computations were obtained from twice-daily radiosonde soundings taken at Albany, New York, and Nantucket, Massachusetts, during July and November 1963. Results indicate that the NBS model does not completely remove height errors, but it can be used effectively to offset errors due to slow seasonal changes in bending conditions. The correction technique is not effective during periods of anomalous propagation. A review of more recent prediction techniques (1963) is presented, and recommendations are made for their field evaluation.

REVIEW AND APPROVAL

This technical report has been reviewed and is approved.

Stanley J. Wisniewski

STANLEY J. WISNIEWSKI
Lt. Colonel, USAF
Director of Sensors

TABLE OF CONTENTS

		Page
LIST OF ILLUSTRATIONS		vii
SECTION I	INTRODUCTION	1
SECTION II	THE NBS SURFACE-CORRECTED MODEL ATMOSPHERE	3
SECTION III	METHOD OF ANALYSIS	5
SECTION IV	RESULTS OF DATA ANALYSIS	6
	CORRELATION OF RADIOSONDE AND MODEL DATA	6
	EQUIVALENT HEIGHT-ERROR DISTRIBUTION	6
	ADDITIONAL ANALYSIS OF LOW-ANGLE DATA	11
	RESULTS USING A HIGHER-ANGLE CASE	18
SECTION V	DISCUSSION OF RESULTS	23
SECTION VI	A COMPARISON OF THE MITRE RESULTS WITH THE NBS ESTIMATES	24
SECTION VII	OPERATIONAL CONSIDERATIONS	27
SECTION VIII	CONCLUSIONS AND RECOMMENDATIONS	28
REFERENCES		29

LIST OF ILLUSTRATIONS

Figure Number		Page
1	Comparison of Radiosonde N Profile with NBS Model Profile	4
2	Comparison of Radiosonde and Model Bending, Albany, July 1963, $\theta_o = 1$ mr, Range of 92 nm	7
3	Auto-correlation of Radiosonde Bending, Albany, July 1963, $\theta_o = 1$ mr, Range of 92 nm	8
4	Cross-correlation between Radiosonde and Model Bending, Albany, July 1963, $\theta_o = 1$ mr, Range of 92 nm	9
5	Ray Bending τ versus Elevation Angle Error ϵ	10
6	Height-Error Distribution, Albany, July 1963, $\theta_o = 1$ mr, Range of 92 nm	12
7	Comparison of Radiosonde and Model Bending, Albany, November 1963, $\theta_o = 1$ mr, Range of 92 nm	13
8	Cross-correlation between Radiosonde and Model Values of τ, Albany, November 1963, $\theta_o = 1$ mr, Range of 92 nm	14
9	Height-Error Distribution, Albany, November 1963, $\theta_o = 1$ mr, Range of 92 nm	15
10	Comparison of Radiosonde and Model Bending, Nantucket, July 1963, $\theta_o = 1$ mr, Range of 92 nm	16
11	Comparison of Radiosonde and Model Bending, Nantucket, November 1963, $\theta_o = 1$ mr, Range of 92 nm	17
12	Height-Error Distribution, Nantucket, July 1963, $\theta_o = 1$ mr, Range of 92 nm	19
13	Height-Error Distribution, Nantucket, November 1963, $\theta_o = 1$ mr, Range of 92 nm	20
14	Comparison of Radiosonde and Model Bending, Albany, July 1963, $\theta_o = 10$ mr, Range of 124 nm	21
15	Height-Error Distribution, Albany, July 1963, $\theta_o = 10$ mr, Range of 124 nm	22

SECTION I

INTRODUCTION

Radio refraction in the lower troposphere continues to undergo intensive investigation due to the increasing precision demanded by advanced electromagnetic systems. The index of refraction varies significantly in the vertical direction. However, Bean and Cahoon[1] have shown it to be almost horizontally stratified for ray-tracing analysis, except in the case of anomalous conditions. The investigations of Bauer, Mason, and Wilson[2] indicated that the vertical variation of the index behaved as an exponential function with height during most of the year in temperate latitudes. Bean and Thayer[3] developed an exponential reference atmosphere based on a large number of radiosonde soundings from climatically and geographically diverse U. S. stations. The results of this latter investigation support the exponential model and also show that a relationship exists between the index at the surface and the average index gradient measured over the first kilometer in height.

Radio ray bending occurs mostly in the lower part of the troposphere where the vertical variation of index is greatest. Therefore, the fact that the initial gradient over the first kilometer can be related to the readily obtainable surface value has great practical significance. Sweezy and Bean[4] evaluated the use of the surface index, initial surface gradient, and first kilometer average gradients to correct radar height errors. The first-order correction only used the surface index N_s. The accuracy was then increased by using both N_s and the initial surface gradient G_o. Finally, the analysis included not only N_s and G_o, but also the gradient $\Delta N/\Delta h$ averaged over the first kilometer in height. More recently, Sweezy and Bean [5] extended their technique into the range of extremely small initial elevation angles.

Towers and radiosonde soundings would be required to determine the surface gradient G_o and the first kilometer average gradient $\Delta N/\Delta h$. These facilities are not normally or conveniently available at most sites. Therefore, this report investigates the use of surface measurements alone to determine ray-path bending and height errors with the 1959 NBS model profile.

Albany, New York, and Nantucket, Massachusetts, were selected for investigation during the months of July and November 1963. The NBS model predictions are compared with determinations of the ray-path bending using radiosonde measurements of the refractivity profile.

SECTION II

THE NBS SURFACE-CORRECTED MODEL ATMOSPHERE

The surface-corrected prediction techniques is based on two empirical findings[3]: on the average, the change in refractivity over the first kilometer in height, ΔN, is related to the surface refractivity, N_s, as follows,

$$-\Delta N = 7.32 \exp(0.005577\, N_s) \;; \tag{1}$$

and, on the average, the radio refractivity N is an exponential function of height. The 1959 NBS exponential reference atmosphere[3] is defined by Equation (2):

$$N = N_s \exp\left[-(h-h_s) \ln \frac{N_s}{N_s + \Delta N}\right], \tag{2}$$

where

h = altitude above mean sea level;

h_s = surface elevation:

and ΔN is given by Equation (1).

Figure 1 shows the exponential model profile generated by a surface refractivity value of 354 N units. Two radiosonde soundings, both having surface refractivity of 354 N units, are also shown. These were taken on July 21, 1963, at Albany, one at 1100 and the other at 2300 Greenwich mean time. It is apparent that the actual refractivity profiles differ from the predicted profile, although the surface refractivity values are the same. These differences in profile mean that the ray-path bending, which is calculated from the predicted (exponential) profile, will differ from the actual bending. The following analysis was made to estimate the practical effect of these differences on height errors.

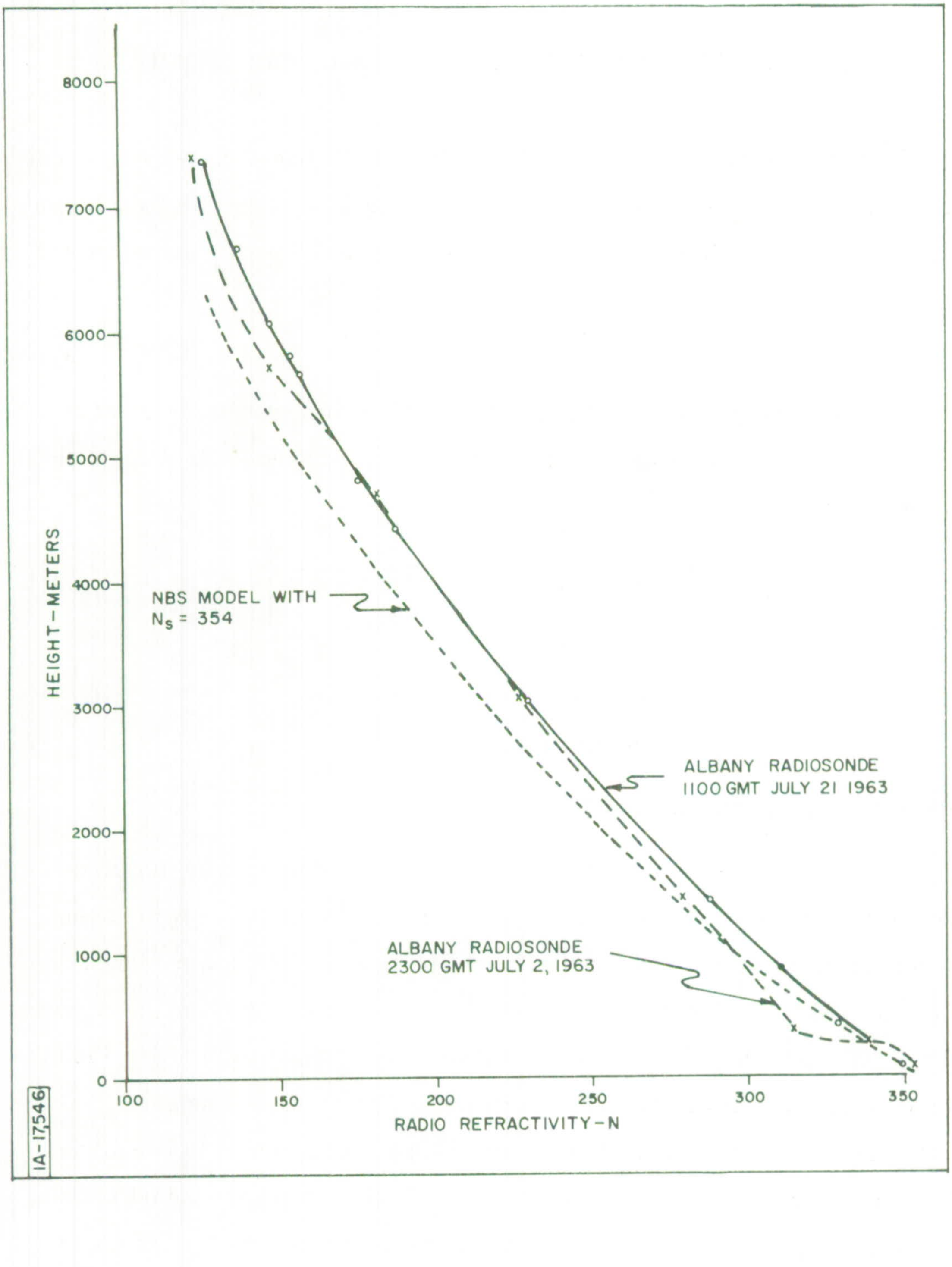

Figure 1. Comparison of Radiosonde N Profile with NBS Model Profile

SECTION III

METHOD OF ANALYSIS

Albany and Nantucket were selected for investigation because they represent two different climates. Albany is well inland, while Nantucket experiences maritime conditions. In fact, anomalous propagation occurs extensively at Nantucket during the summer months. Two radiosonde soundings were made each day at both sites with launch times at 1100 and 2300 Greenwich mean time. Using the data from these soundings in a ray-tracing computer program, the ray-path bending was then computed for each site. In the first part of this analysis, the initial elevation angle of the ray was taken to be 1 milliradian, which represents a near-horizon propagation condition. Under normal propagation conditions, the ray would be about 6500 feet above the earth's surface after traveling a distance of 92 nautical miles. The Albany soundings were then used to calculate the bending for a ray with an initial elevation angle of 10 milliradians (corresponding to a ray height of 16,500 feet at a distance of 124 nautical miles under normal propagation conditions).

For each radiosonde sounding, the surface index of refraction was used with the 1959 NBS model to calculate the bending. By comparing the data, it was possible to evaluate the accuracy of this model.

SECTION IV

RESULTS OF DATA ANALYSIS

CORRELATION OF RADIOSONDE AND MODEL DATA

The first analysis of data considers the low-angle propagation cases where the initial elevation angle θ_o is 1 milliradian. Figure 2 shows the predicted and the calculated bending τ plotted against days during July at Albany. There are obvious differences between the curves; however, the average of the predicted values appears to follow the trend towards slightly increased bending as the days progress.

A computer program was used to determine the auto-correlation function for the bending values calculated from the radiosonde profiles. This function is shown in Figure 3, and it is apparent that the correlation length is about one-half day. This observation is somewhat dependent upon the one-half-day sampling rate.

The normalized cross-correlation function was determined for the radiosonde and model values shown on Figure 2. This function (seen in Figure 4) indicates there is a 70 percent correlation at zero time delay. This high degree of correlation indicates that the model values closely follow the variations in propagation conditions.

EQUIVALENT HEIGHT-ERROR DISTRIBUTION

From the large number of ray-tracing calculations, a graphical relationship was established between the overall bending τ and the elevation error ϵ. In the range of interest from about 4 to 14 milliradians of accumulated bending (see Figure 2), the relationship between τ and ϵ is approximated by a straight line as shown in Figure 5.

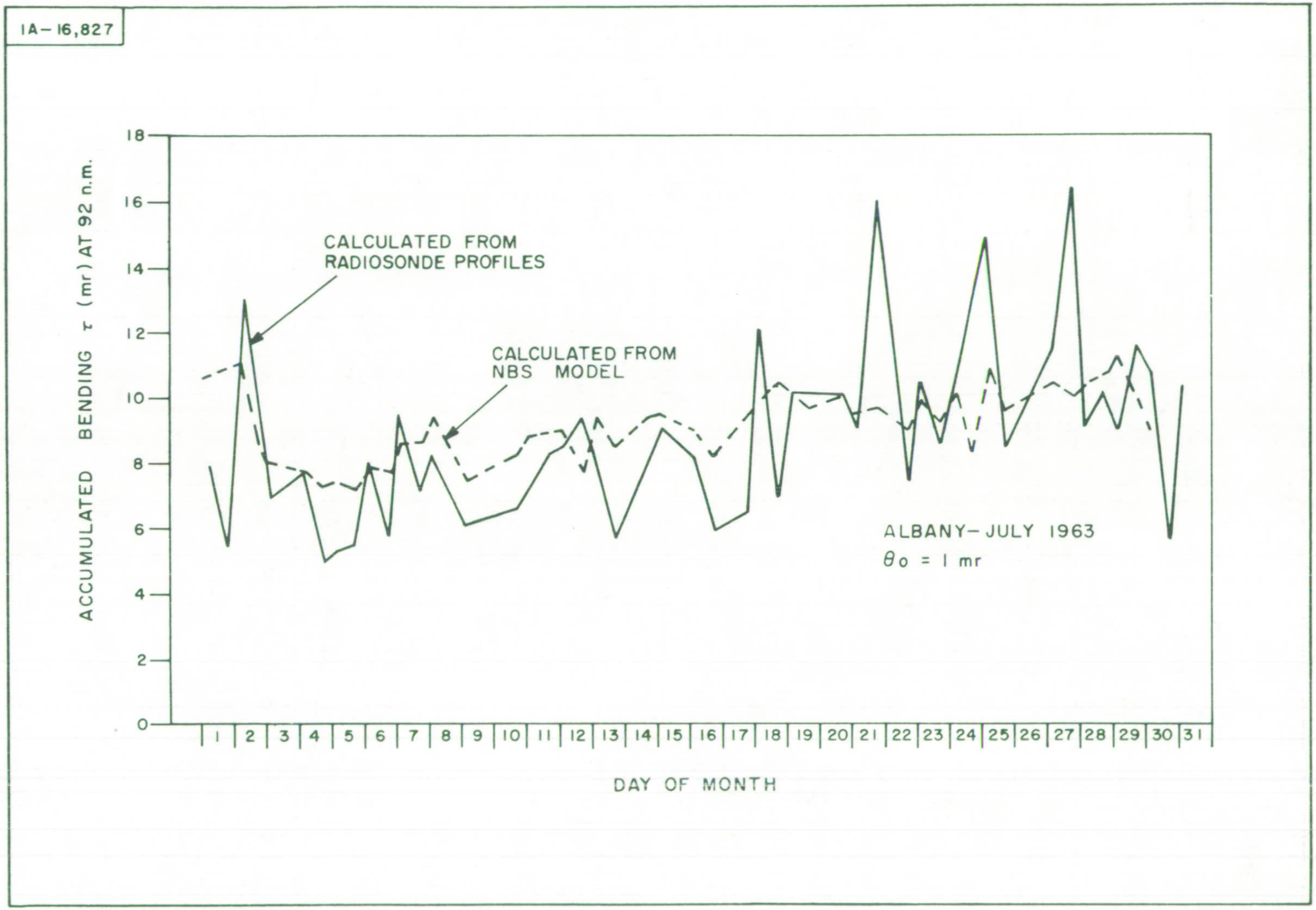

Figure 2. Comparison of Radiosonde and Model Bending, Albany, July 1963, θ_o = 1 mr, Range of 92 nm

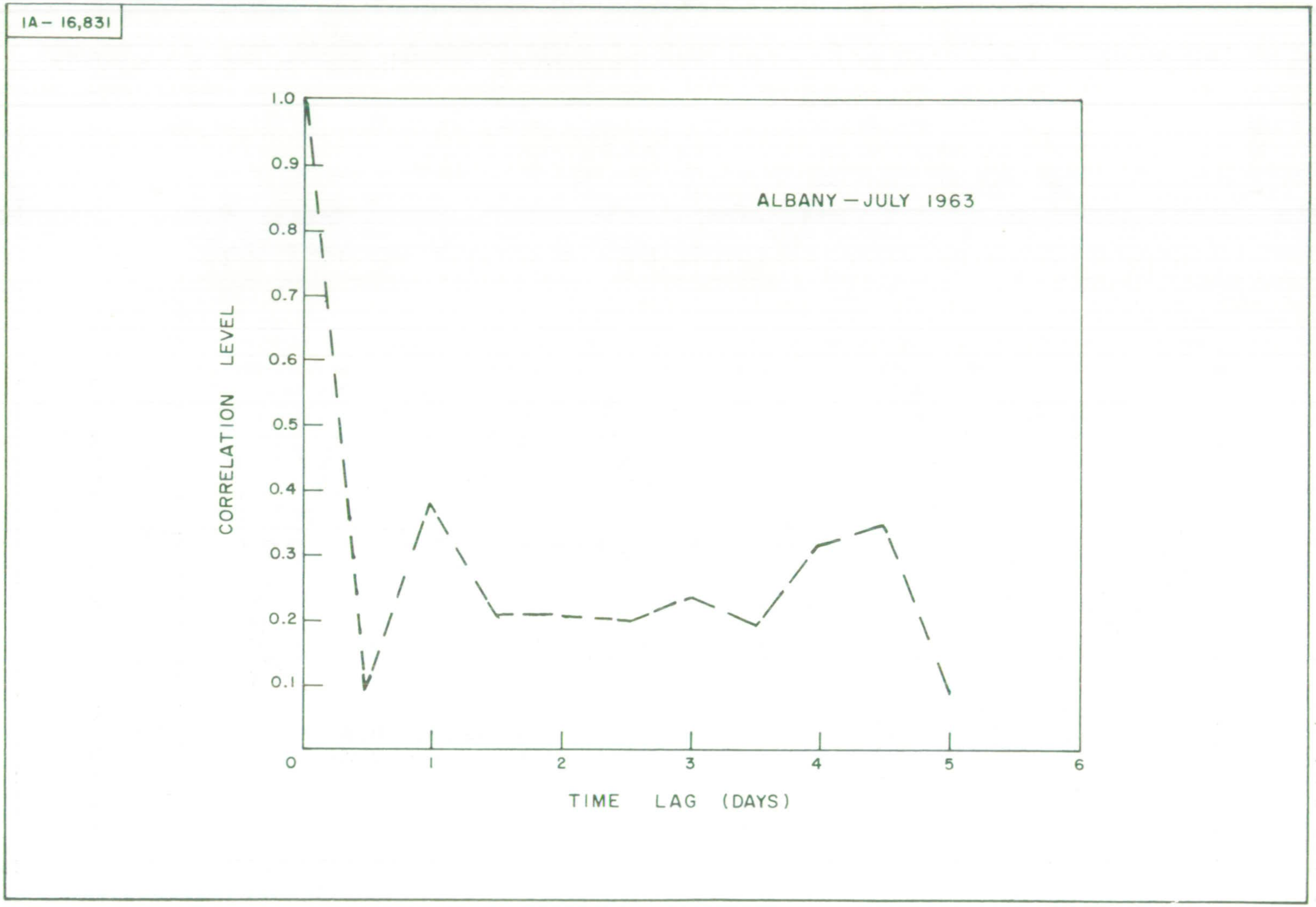

Figure 3. Auto-correlation of Radiosonde Bending, Albany, July 1963, $\theta_o = 1$ mr, Range of 92 nm

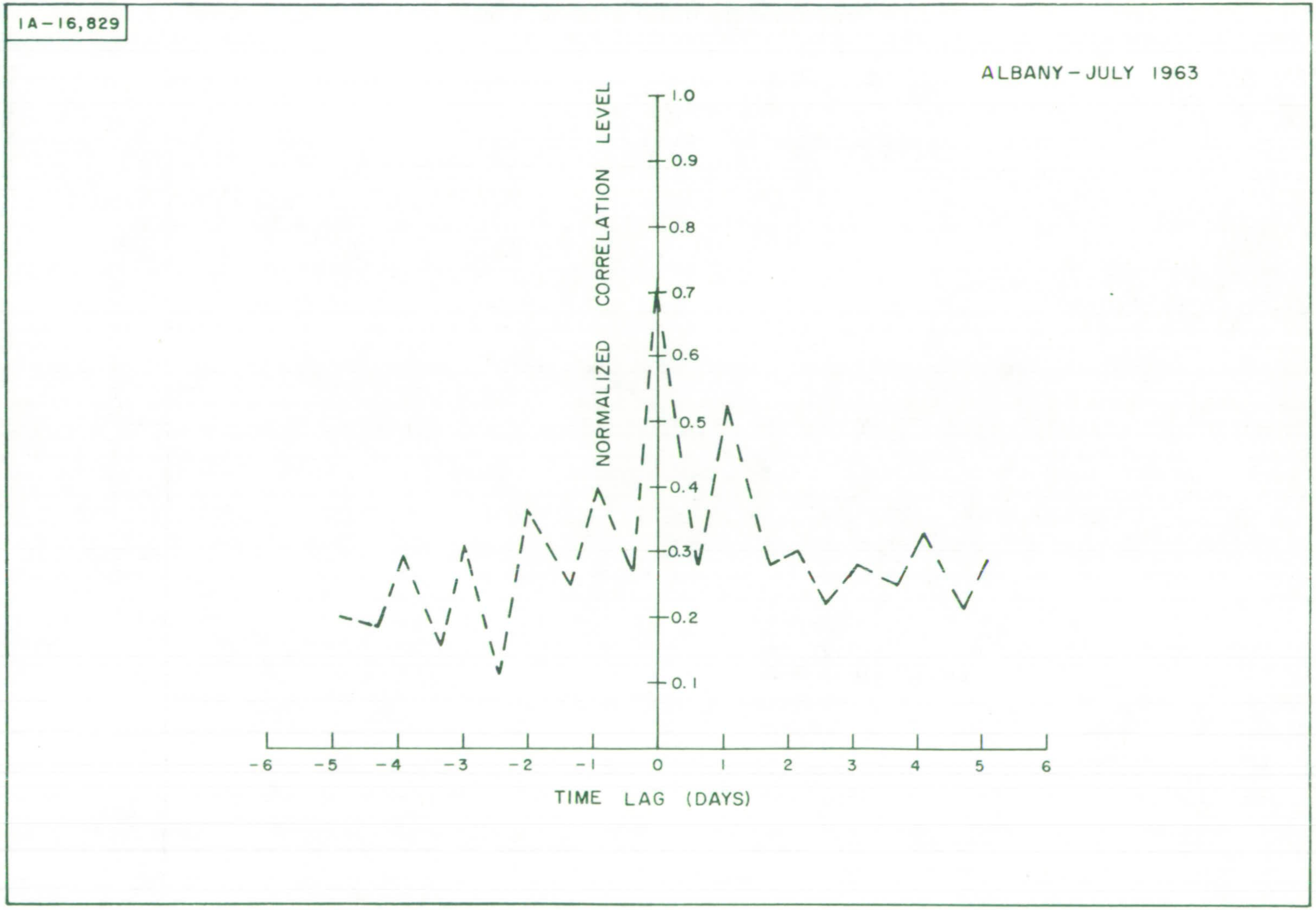

Figure 4. Cross-correlation between Radiosonde and Model Bending, Albany, July 1963, $\theta_o = 1$ mr, Range of 92 nm

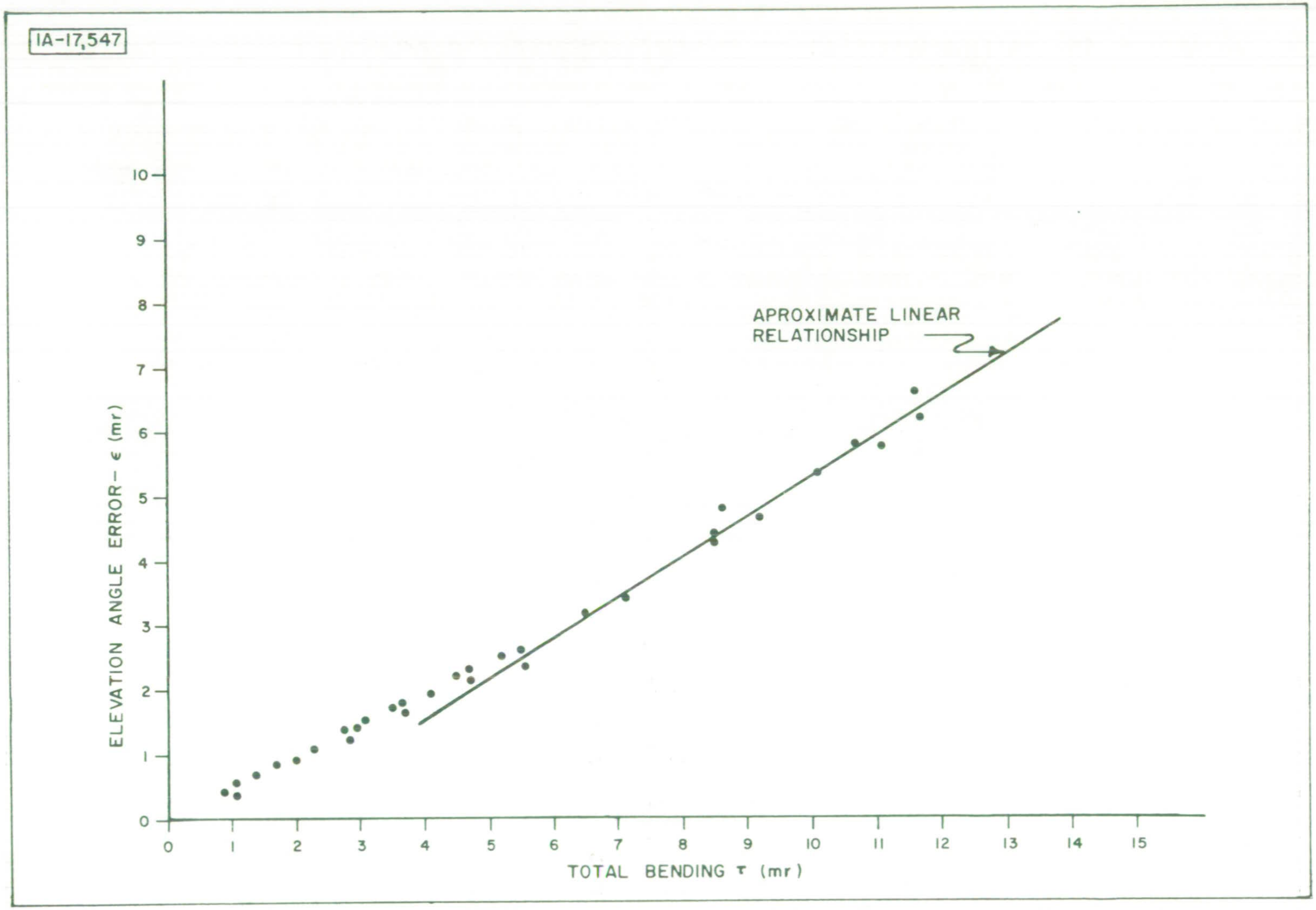

Figure 5. Ray Bending τ versus Elevation Angle Error ϵ

Thus, the uncorrected bending $\Delta\tau$ can be related to an uncorrected elevation angle error $\Delta\epsilon$. The height error can then be determined by multiplying $\Delta\epsilon$ by the range. Using the above relationship, the uncorrected bending errors $\Delta\tau$ between radiosonde and model values were translated into a height-error distribution. Figure 6 shows this error distribution curve for Albany during July 1963. The percentage of the height errors which were less than a specified error $|\Delta h|$ are plotted against $|\Delta h|$. For example, 50 percent of all the residual height errors are less than $\pm$400 feet; or, in operational terms, there is 50 percent confidence that in this situation the height error is less than $\pm$400 feet. If the confidence requirement is set higher, the probable height error is correspondingly greater.

ADDITIONAL ANALYSIS OF LOW-ANGLE DATA

Similar analyses were made of the low-angle data for Albany during November and for Nantucket during July and November 1963. Figure 7 shows the radiosonde and model bending for Albany during November, and Figure 8 shows the cross-correlation function for these data. It is apparent that there is little, if any, correlation during this month. However, the residual height-error distribution (Figure 9) indicates that the errors averaged over November do not differ essentially from those at Albany during July (Figure 6).

The comparisons of radiosonde and model bending at Nantucket for July and November are shown in Figures 10 and 11, respectively. The radiosonde results show that anomalous propagation is very prevalent during July. The large values of bending and the frequent occurrences of trapping are evidence of the strong influence the ocean has on such coastal sites. In this type of situation, the model which uses only the surface index is insufficient for making accurate calculations of bending. The height-error distribution curves for Nantucket in July and November are shown in Figures

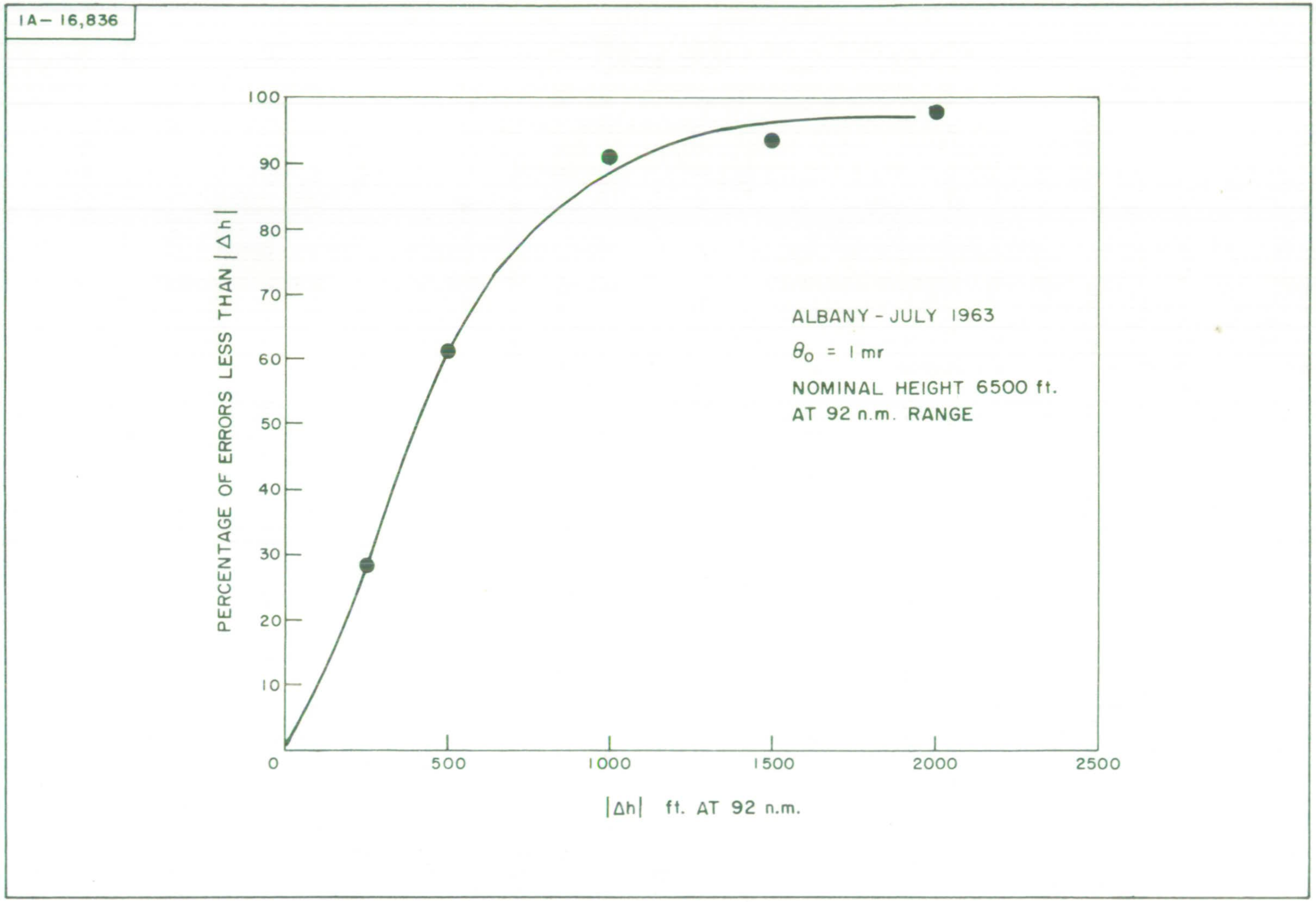

Figure 6. Height-Error Distribution, Albany, July 1963, $\theta_o = 1$ mr, Range of 92 nm

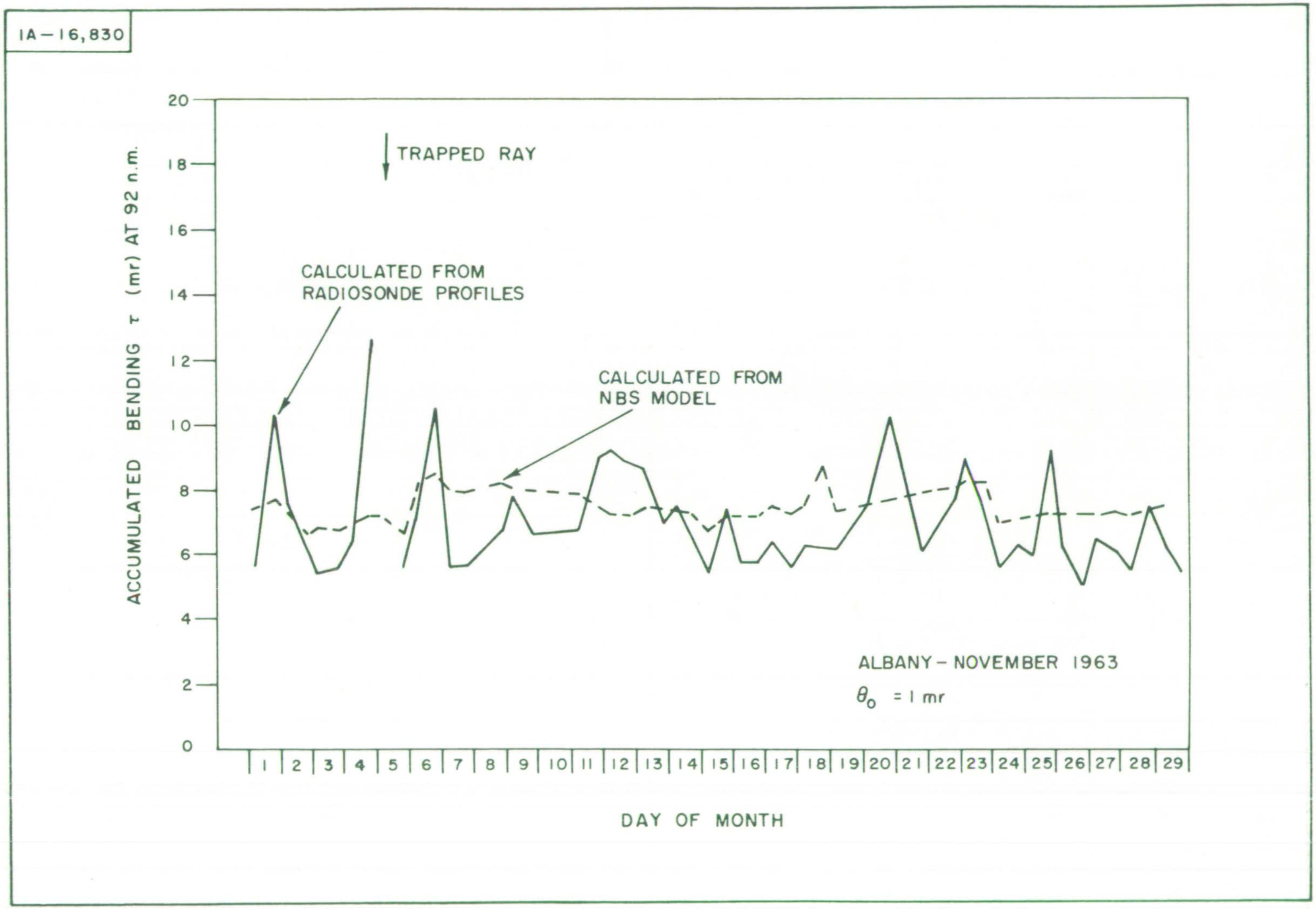

Figure 7. Comparison of Radiosonde and Model Bending, Albany, November 1963, $\theta_o = 1$ mr, Range of 92 nm

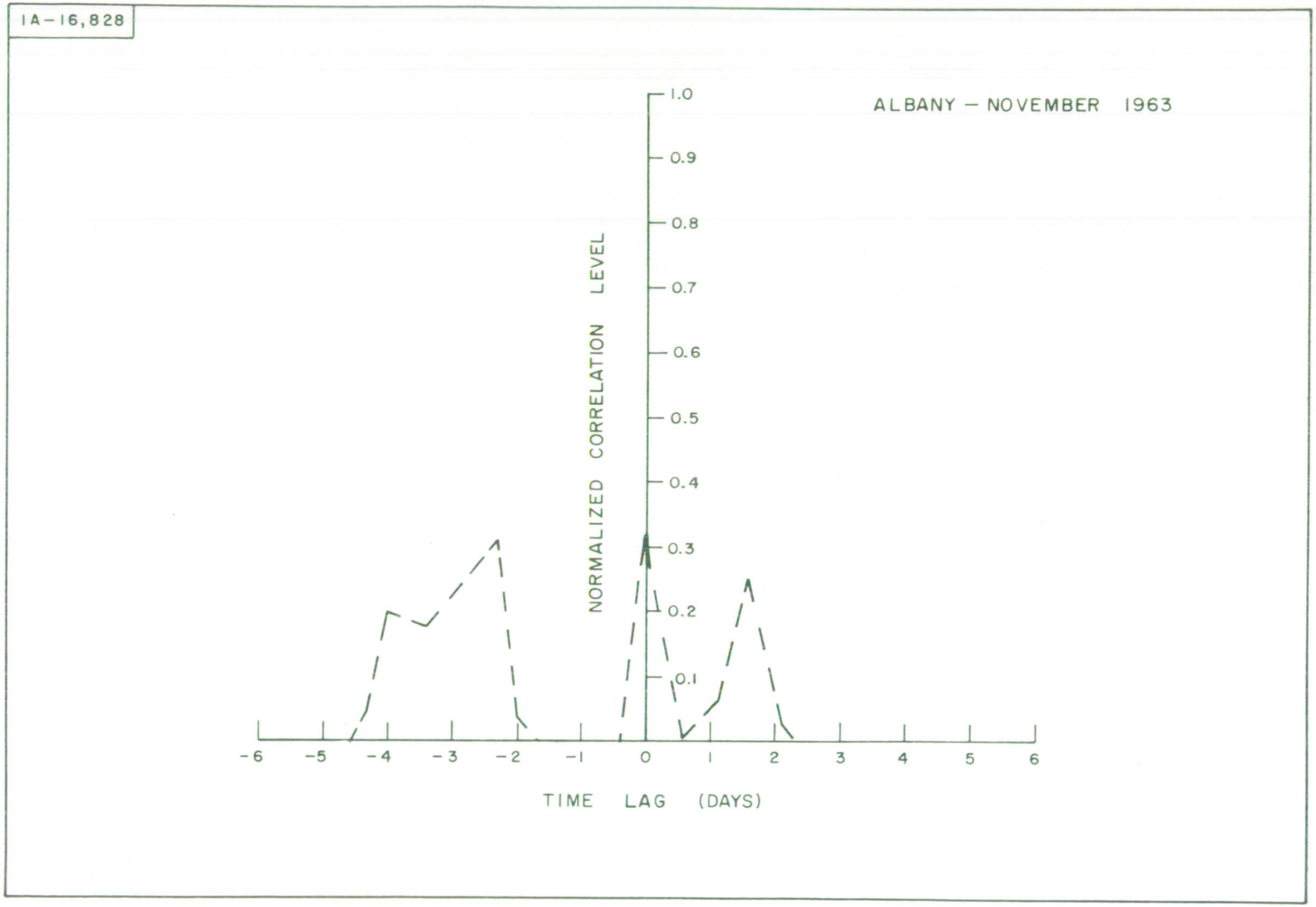

Figure 8. Cross-correlation between Radiosonde and Model Values of τ, Albany, November 1963, $\theta_o = 1$ mr, Range of 92 nm

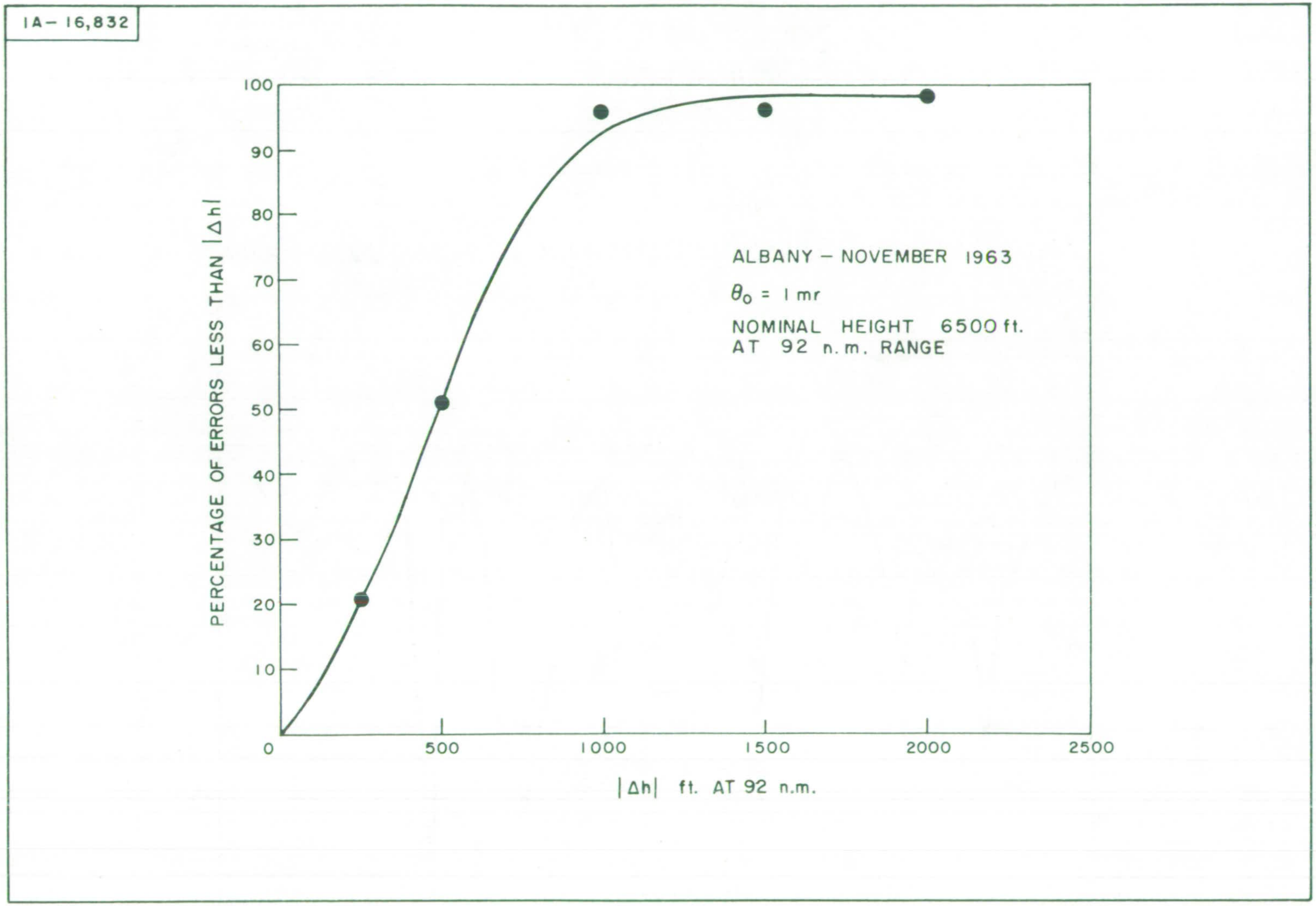

Figure 9. Height-Error Distribution, Albany, November 1963, θ_o = 1 mr, Range of 92 nm

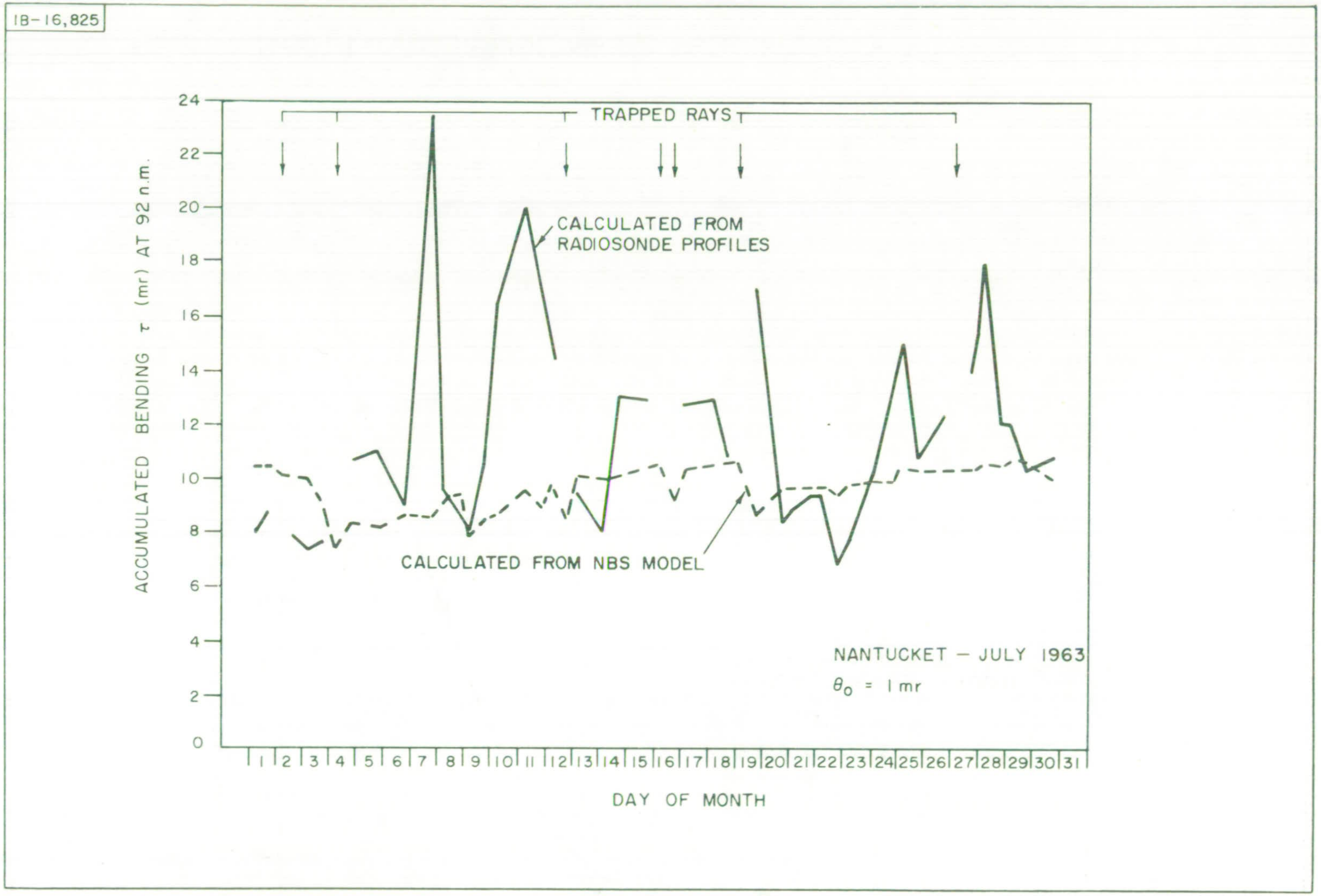

Figure 10. Comparison of Radiosonde and Model Bending, Nantucket, July 1963, $\theta_o = 1$ mr, Range of 92 nm

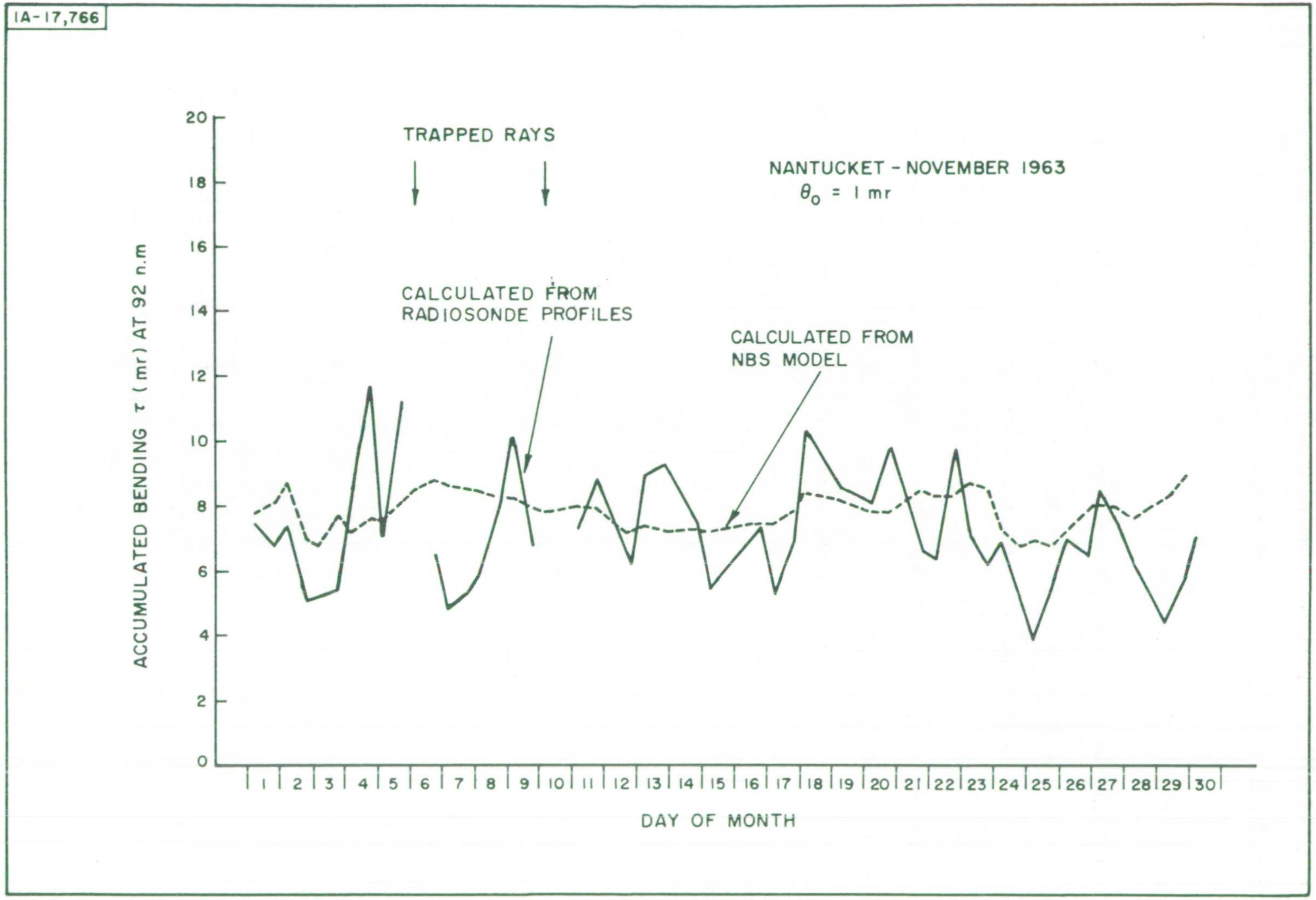

Figure 11. Comparison of Radiosonde and Model Bending, Nantucket, November 1963, θ_o = 1 mr, Range of 92 nm

12 and 13. As Figure 12 shows, there is a marked reduction in height accuracy due to the anomalous propagation conditions during July.

RESULTS USING A HIGHER-ANGLE CASE

A comparison of radiosonde and model bending was made using the Albany data for July but with an initial elevation angle of 10 milliradians (Figure 14). It is apparent that the model follows the trend towards higher bending as the days progress. The corresponding height-error distribution is shown in Figure 15. A comparison with Figures 6, 9, and 13 shows that the errors for $\theta_o = 10$ milliradians are about one-half the errors with $\theta_o = 1$ milliradian and for normal propagation conditions.

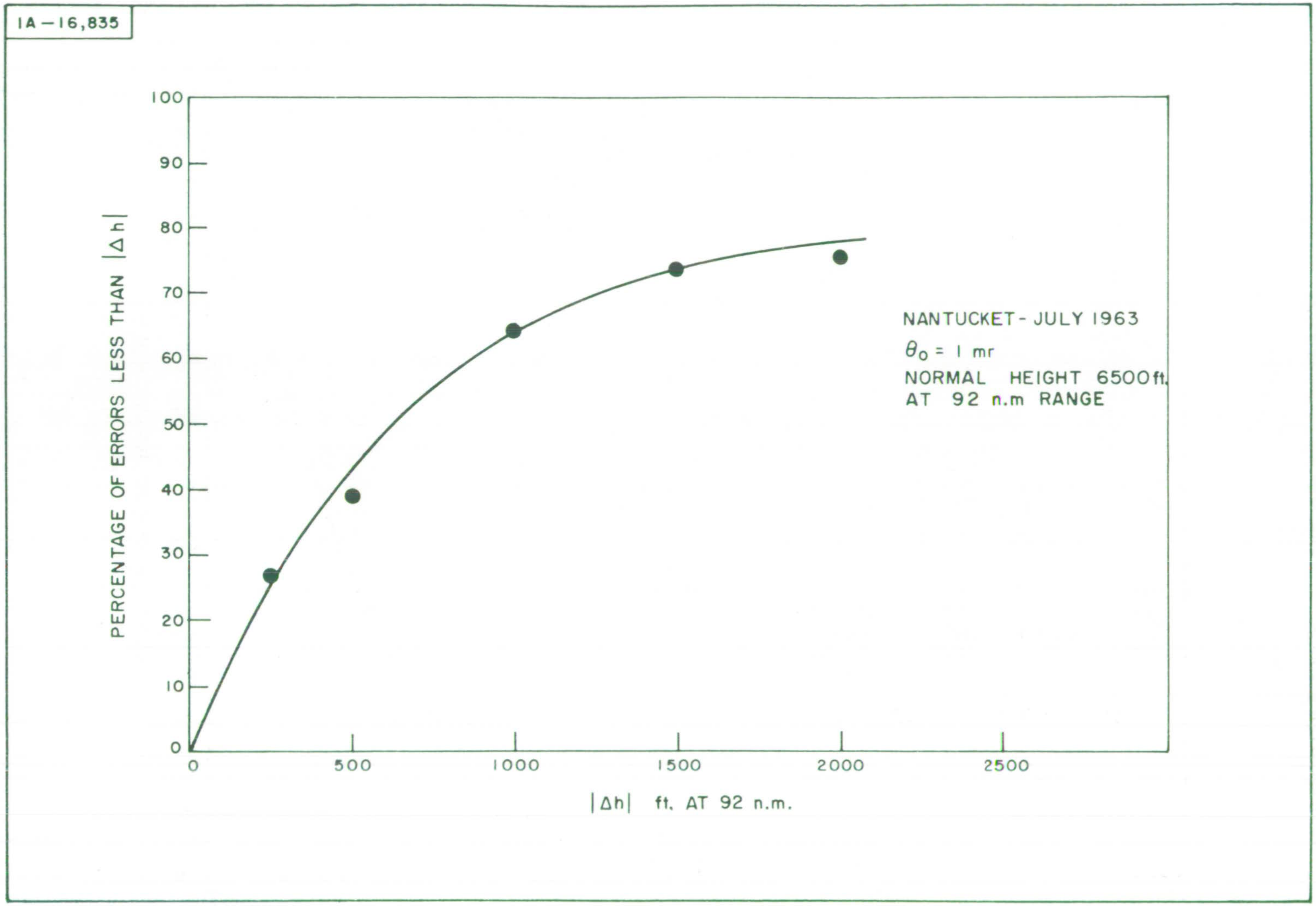

Figure 12. Height-Error Distribution, Nantucket, July 1963, $\theta_o = 1$ mr, Range of 92 nm

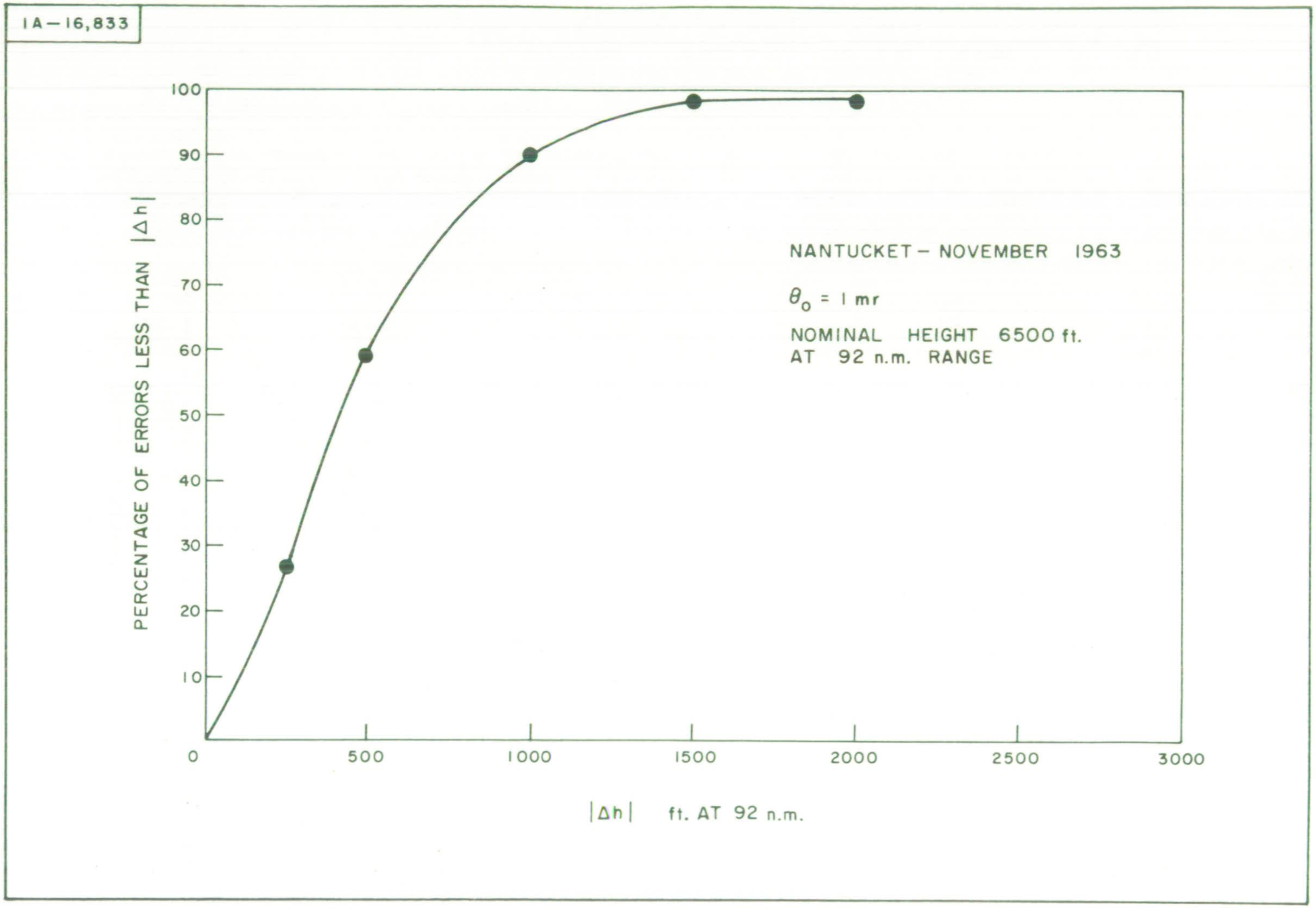

Figure 13. Height-Error Distribution, Nantucket, November 1963, $\theta_o = 1$ mr, Range of 92 nm

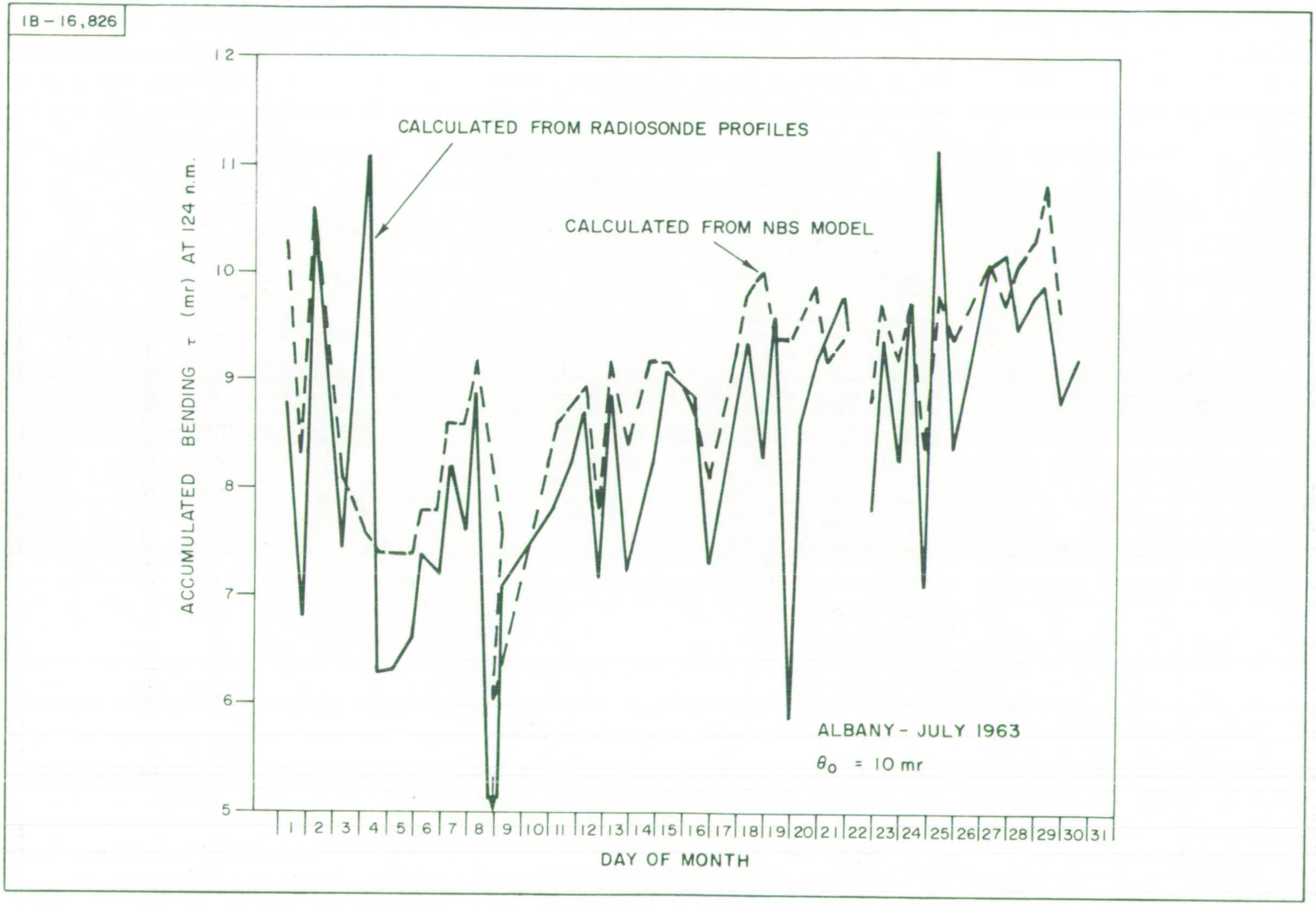

Figure 14. Comparison of Radiosonde and Model Bending, Albany, July 1963, $\theta_o = 10$ mr, Range of 124 nm

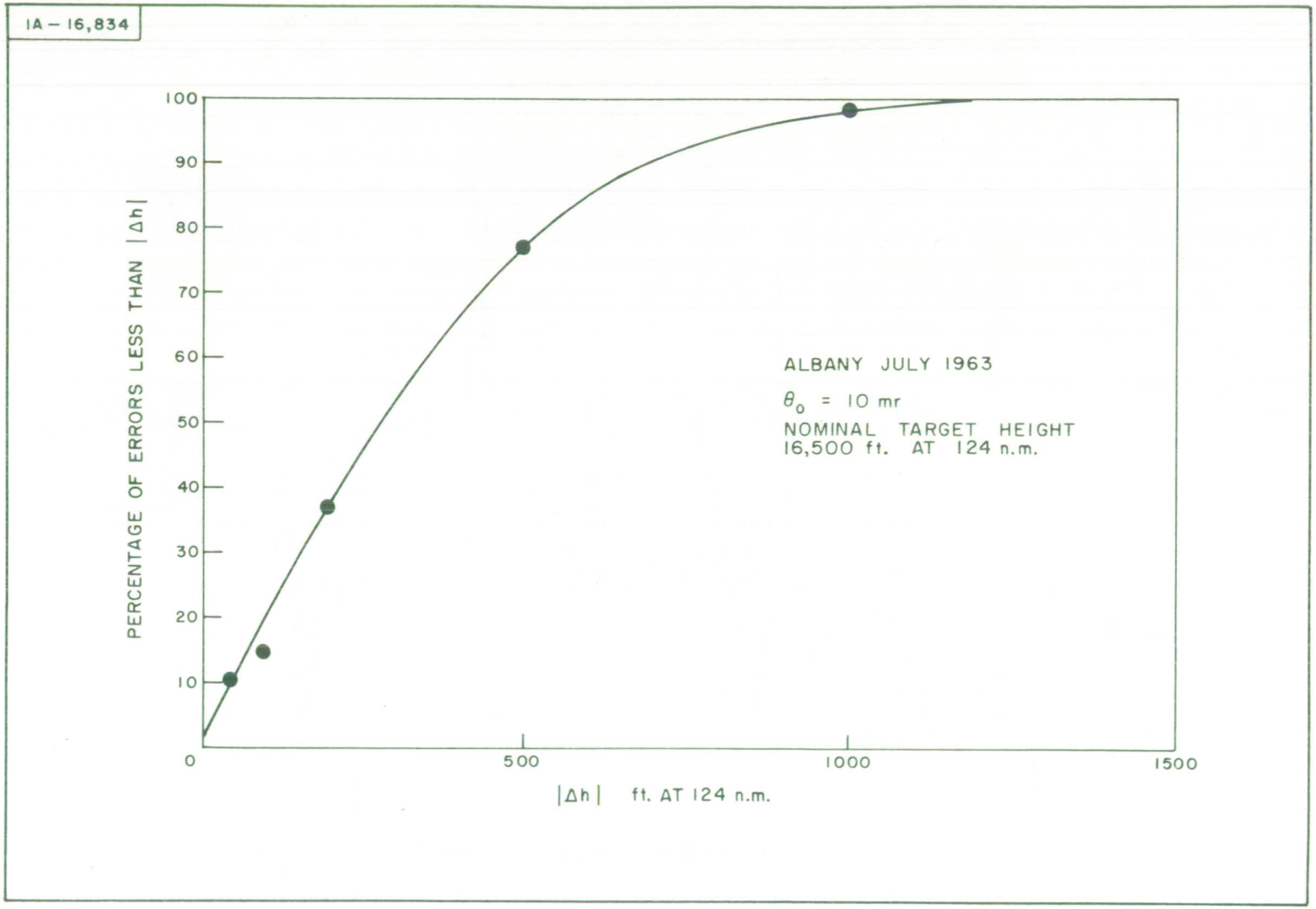

Figure 15. Height-Error Distribution, Albany, July 1963, $\theta_o = 10$ mr, Range of 124 nm

SECTION V

DISCUSSION OF RESULTS

It is apparent from the preceding analysis that the surface-corrected exponential model provides a satisfactory basis for making first-order height-error corrections except under abnormal refraction conditions. Although it does not completely remove height errors, it can be used to offset errors due to slow seasonal changes in bending conditions.

Recent discussions with Bean and Sweezy (August 13, 1965, at Central Radio Propagation Lab., NBS, Boulder, Colorado) were concerned with improved methods to obtain height-error reductions at the low elevation angles. The technique using surface index and initial gradient data was first reported in 1963.[4] As seen in Table I, the attempt to extrapolate this method to the low angles would appear to provide results essentially similar to those obtained by The MITRE Corporation. However, Bean and Sweezy stressed that such an extrapolation could become erroneous, and they recommended reference to their later methods for low-angle bending corrections reported in October 1963.[5]

SECTION VI

A COMPARISON OF THE RESULTS OF THE MITRE CORPORATION WITH THE NBS ESTIMATES

Table I shows the height errors obtained at Albany and Nantucket using the exponential reference atmosphere.[3] The 68 percentage level on the error distribution curves was selected. The listed height errors then represent observations with ± 1 standard deviation of the mean height error. The extrapolated results using the NBS curves are also shown for comparison, although it is recognized that the NBS analysis was not intended to cover these low-angle cases.[4] Finally, the latest NBS results are shown using the low-angle correction techniques.[5] The locations analyzed in this latter report were selected because they represent climatic extremes.

From the tabulated results of NBS and the analysis of the 13 climatically different sites, the use of initial gradient data G_o appears to reduce the height error from that obtained using the surface value, N_s, alone. With the latest correction technique,[5] the low-angle NBS data shows a marked reduction in height error. The use of initial gradient data, G_o, does not always contribute to an increase in accuracy.

Table I

Comparison of Height-Error Results

MITRE Data			Extrapolated NBS Data			Low-Angle NBS Data		
θ_o = 1 mr, Range = 92 nm, Height = 6500 ft. (nominal)								
Location	1963 Date	Error Using N_s (ft.)	Location	Error Using N_s (ft.)	Error Using $N_s + G_o$ (ft.)	Location	Error Using N_s (ft.)	Error Using $N_s + G_o$ (ft.)
Albany	July	580	Selected profiles from 13 climatically different sites	450	300	Miami, Fla.	56	178
Albany	Nov.	680				Columbia, Miss.	35	99
Nantucket		1180				Denver, Colo.	29	162
Nantucket		600				Canton Island, Central Pacific	245	99
						Isachsen, N. W. T.	451	180

Table I (Concluded)

Comparison of Height-Error Results

MITRE Data			Extrapolated NBS Data			Low-Angle NBS Data		
θ_o = 10 mr, Range = 124 nm, Height = 16,500 ft. (nominal)								
Location	1963 Date	Error Using N_s (ft.)	Location	Error Using N_s (ft.)	Error Using $N_s + G_o$ (ft.)	Location	Error Using N_s (ft.)	Error Using $N_s + G_o$ (ft.)
Albany	July	420	Selected profiles from 13 climatically different sites	350	260	Miami, Fla.	26	102*
						Miami, Fla.	74	75†
						Columbia, Miss.	77	160**
						Denver, Colo.	79	166***

* = Range 107 nm, Height 16,600 ft.
† = Range 130 nm, Height 23,000 ft.
** = Range 103 nm
*** = Range 99 nm

SECTION VII

OPERATIONAL CONSIDERATIONS

It has been demonstrated that by the use of the NBS exponential reference atmosphere, the magnitude and direction of the average changes in bending over a one-month period can be predicted. The daily variations were not always predicted; however, this result was not unexpected due to the extreme variations which occur near the earth's surface. Ringwalt[6] reported that surface index changes as much as 15 N units in 20 miles distance were measured in Florida.

Discussions with Sweezy (August 13, 1964, at CRPL, NBS) indicated that tower measurements might be the most effective way to provide an initial gradient measurement and a meaningful estimate of the surface index. For example, a two-point measurement above the surface could be extrapolated to give a representative surface value. These measurements might be made using the radar structure to obtain some initial height advantage. Although this question of minimizing local ground variations does not appear to represent any technical difficulty, there is possibly an economical problem. Having obtained the correct measurement, there is the remaining and most difficult problem of how to use the information with available field equipment. To apply the corrections would require modifications to display systems and/or data-processing facilities, which might be centralized so as to serve several sites. These economical questions cannot be answered without further study and are beyond the scope of this report.

SECTION VIII

CONCLUSIONS AND RECOMMENDATIONS

The results of this investigation, coupled with the development of more exact analysis, indicate that height-error corrections methods are available to meet the requirements of most users. Excluding the need for fine structure, for example, at the Eastern Test Range, the use of realistic surface and initial gradient data could reduce height errors to a satisfactory level.

There are remaining questions which could best be answered by an error study at a few selected sites. Such a study would require representative surface and initial gradient data supplemented by local radiosonde data and aircraft measurements. The extent of horizontal surface variations would be investigated to determine if the index measurements could be meaningfully applied in the correction system. An aircraft at a known height could be used to obtain radar height measurements. The correction technique would then be applied to each test mission to evaluate the method and usefulness of the surface and initial gradient measurements in reducing height errors.

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13. ABSTRACT

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